Strain shielding 12 weeks after femoral reaming and nailing in rats

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The purpose of this study was to investigate the in vivo strain-shielding in rat femora 12 weeks after intramedullary nailing with either flexible or rigid implants. Five days prior to death, unidirectional strain gauge units were implanted on the anterior bone surface bilaterally. Median strain values of reamed only and polyacetal-nailed femora ranged from 67 to 90 percent of the intact side. Removal of polyacetal nails and sham operations gave negligible changes in strain. Strain of the steel-nailed femora was 51 percent of the intact side. Removal of nails increased strain to 91 percent of the intact side.

Testing of femora after removal of implants revealed stiffness of 116 and 103 percent of normal in reamed-only and polyacetal-nailed groups, respectively. Stiffness in the steel-nailed group was reduced to 85 percent of normal. None of these changes were statistically significant.

This study indicates that rigid intramedullary nails cause strain shielding at the anterior, mid-diaphyseal surface of rat femora 12 weeks after insertion. Removal of rigid implants seems to restore the loading configuration immediately.

Little is known about the stress-strain-shielding effect of intramedullary nails of different rigidity. Excess rigidity has been found to cause a scant callus with early signs of maturation in fracture healing, but low strength and deformation at fracture (Brown and Mayor 1978, Klopper and Tonino 1980, Wang et al. 1981, Mølster et al. 1982). No differences in mechanical properties were observed when flexible and rigid intramedullary nails were used for fracture fixation (Christel et al. 1984). On the other hand, rigid intramedullary nails in intact rat femora have been reported to induce lower values of strength and energy absorption (toughness) at 6 months than did flexible nails or reaming only (Mølster 1986). In our previous in vivo investigation, the immediate effect of steel nailing following reaming of intact rat femora was a pronounced decrease in strain at the mid-diaphyseal level (Husby et al. 1989). The immediate effect of reaming or reaming combined with flexible nails was small.

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We have studied the in vivo strain shielding in rat femora 12 weeks after nailing with either flexible or rigid implants.

Material and Methods

Experimental design

Thirty-seven male 8-week-old 200–265 g Wistar rats were caged separately and given water and standard animal pellets ad libitum. All the animals had their right femoral medullary cavities reamed, and they were randomized into three groups: in Group A (n 12) polyacetal nails were then inserted; in Group B(n 12) steel nails were used; and for Group C (n 13) only reaming was done. Twelve weeks after reaming/nailing, strain gauges were implanted in both left and right femora of each animal, and in vivo strain was recorded. Two days later, the nails were removed (Groups A and B) or a sham operation was performed (Group C) and the strain measurements were repeated.

The animals were then killed, and in vitro load/strain measurements were performed on the excised femora (Figure 1). In addition, a bending test was performed on six intact femora from 8-week-old rats, six intact femora from 20-week-old rats, six polyacetal nails, and six steel nails.

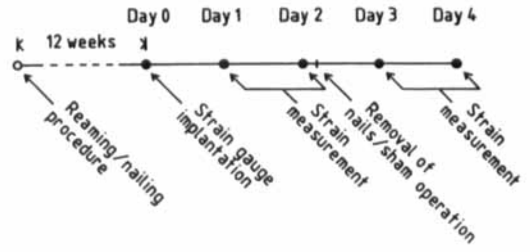

Figure 1. Chronology of the operative procedures and in vivo strain measurements.

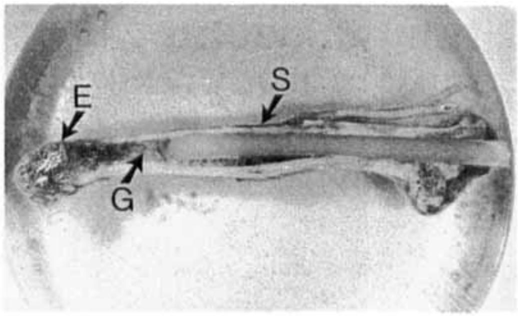

Figure 2. Longitudinal ground section of the femur through the center of strain gauge (S). A gap (G) is seen between the distal end of the polyacetal nail and the distal epiphyseal plate (E).

The reaming and nailing procedure was performed as described by Husby et al. (1989). Group A received flexible nails made of polyacetal polymer and Group B received stiff nails made of solid stainless steel. No nails were used in Group C. Intact femora had a median stiffness at the beginning of the experiment of 285 (218–322) N/mm and after 12 weeks 682 (598–721) N/mm.

The animals tolerated intramedullary reaming and nailing well, and the function of the operated on limb appeared normal from the recovery after anesthesia. No infections were observed. Twelve weeks later, when the animals were killed, no loosening of the nails was observed. Ground sections of nailed femora showed a tight-fit connection between nail and bone along the entire length of the nail. Due to longitudinal growth of the femur, a considerable gap was observed between the growth plate and the distal end of the nail (Figure 2). Three animals in group A (polyacetal) died under anesthesia when the strain gauges were implanted, and were excluded from the study.

In vivo strain measurement

Strain gauges were implanted as described previously (Husby et al. 1989) 12 weeks after the reaming and nailing procedures. The upper, lateral corner of the gauge was positioned at the site where the trochanteric edge merged with the shaft. The resistance grid of the gauge was positioned parallel to the long axis of the femur. Gauges that were displaced more than 0.5 mm medially or laterally or rotated more than 10 degrees were repositioned. A 5-mm incision was made in the skin of the rat's neck just distal to the ears, and connection wires were passed through a subcutaneous tunnel to the implantation site. The wounds were closed, and the neck connector fixed to the skin with polyamide sutures. No limp was observed on the first day after strain-gauge implantation. At the end of the experiment, 54 strain gauges were intact. Measurements were not obtained from two gauges at day 4, because pronounced electrical disturbances appeared (Table 1).

In vivo-strain measurements were made while the rats walked on a treadmill at a speed of 10.2 m/min. Measurements were taken for a 1-min period each day. The peak-to-baseline values of 30 walking cycles were measured from each strain recording; the arithmetic mean represented absolute changes in dynamic strain at the compressive side of the bone during walking.

Removal of nails. Sham operation

Two days after strain-gauge implantation, the right femoral shaft of all the animals was approached through the previous incision made 2 days earlier. The greater trochanter was exposed by dividing m. tensor fasciae latae longitudinally. For nailed femora, the shaft was fixed distally to the gauge and the nail extracted. The fascia and skin were then closed with polyamide sutures.

It was necessary to use high forces in order to extract nails from the femora. One polyacetal nail and four steel nails could not be extracted without severe trauma or fracture, and these animals were killed. Consequently, further recordings were not obtained. One animal in the reamed group (C) refused to walk during the first recording. Another animal in the polyacetal group (A) appeared to walk with a left-sided limp on Day 4. Measurements from these cases were not made at these days.

After the rats had been killed, the femora were tested mechanically and prepared ground sections as described previously were made (Husby et al. 1989).

Presentation of data and statistics

Values from operated on femora were expressed as a percentage of the corresponding values of the intact

Table 1. Median strain values ($x10^{-6}$) from right (operated on) and left (intact) femora, recorded in vivo 1, 2, 3 and 4 days after gauge implantation (lower-upper quartiles)

	Before removal/sham				After removal/sham			
	Operated on side		Intact side		Operated on side		Intact side	
Days	1	2	1	2	3	4	3	4
A	251	262	298	310	235	239	327	298
	(208–277)	(214–300)	(261–351)	(257–384)	(214–297)	(198–284)	(295–382)	(262–367)
n	9	9	9	9	8[b]	7[c]	8[b]	6[c,d]
B	164	159	312	325	266	264	252	272
	(121–200)	(115–194)	(244–358)	(243–358)	(205–302)	(187–326)	(209–350)	(228–367)
n	12	12	12	12	8[b]	8	8[b]	6[c,d]
C	246	237	276	284	240	230	299	312
	(221–323)	(211–301)	(238–337)	(265–339)	(210–310)	(211–308)	(253–358)	(265–336)
n	12[a]	13	12[a]	13	13	13	13	12[d]

Group A Reamed, polyacetal nail. Group B Reamed, steel nail. Group C Reamed only. n = number of valid observations. [a]One animal refused to walk. [b] Five animals (A:1, B:4) were killed because of surgical trauma. [c]One animal walked with a limp. [d]Two gauges (A:1, C:1) showed electrical disturbances.

side. All the results are presented as median values with upper and lower quartiles. Paired differences between strain at Days 2 and 4 were chosen to represent the effect of removal/sham procedures, and were statistically tested. Measurements on different days were similarly compared by the Wilcoxon two-sample test. The three groups were compared by the Kruskal-Wallis test. All the recordings were tested for difference from 100 percent by the Wilcoxon one-sample test. A P-value < 0.05 was considered significant.

Results

In vivo

The strain of the polyacetal-nailed or reamed femora did not differ from the control side at Day 2. For the steel-nailed group the strain was 49 percent lower compared with the control side ($P < 0.005$). Removal of polyacetal nails and sham operations gave changes in strain that were negligible from normal. On the other hand, removal of steel nails increased strain from 51 percent at Day 2 to 91 percent at Day 4, when none of the groups had strains that were discernible from normal, nor did the nailed groups differ from the reamed group. No differences in strain were found between Days 1 and 2, nor between Days 3 and 4. The Kruskal-Wallis test revealed no differences between strain values of intact femora at Days 1 through 4 for the three groups (Table 1).

In vitro

Twelve weeks after the reaming and nailing procedures, there were no group differences in stiffness judged by the Kruskal-Wallis test (Table 2).

Discussion

Rigid intramedullary nails were found to cause strain shielding in the anterior, mid-diaphyseal region of rat femora 12 weeks after insertion, but no change in stiffness due to strain shielding was demonstrated in this study. The small changes in strain values of the intact

Table 2. Median stiffness values ($mN/10^{-6}$) from right (operated on) and left (intact) fat femora recorded after 12 weeks (lower-upper quartiles)

Group	n	Operated on side	Intact side
A	9	41	36
		(30–45)	(33–45)
B	9	35	41
		(29–51)	(31–53)
C	13	36	36
		(30–53)	(29–38)

Reamed, polyacetal-nailed (Group A). Reamed, steel-nailed (Group B). Reamed (Group C).

femora during the observation period of 4 days revealed a negligible effect of the gauge implantation procedure on the strain recordings. Thus, reproducibility of the in vivo measurements was demonstrated.

The steel-nailed group differed markedly from the two other groups when evaluated 12 weeks after the insertion of implants. With the nails in situ, the femora of this group exhibited a low strain level. When the nails were removed, an immediate increase in strain followed. Restricted weight bearing due to pain may have had an effect on the in vivo strain measurements, and the distribution of stress and resulting strain over the cross section may have been altered after the nails had been removed. However, the surgical trauma was similar in all the groups, and the sham procedure did not seem to affect the recordings. Moreover, the small change in strain following removal of polyacetal nails may demonstrate the negligible effect of altered strain distribution due to a spacing effect by the implants. Thus, the dominant increase in strain following removal of the implants shows the strain-shielding effect of the rigid nail. Intramedullary nails, in this respect, act in part similarly to the femoral stem of a hip prosthesis (Lanyon et al. 1981, Cook et al. 1982).

The absolute strain values of the steel-nailed femora were about twice the corresponding values recorded immediately after reaming and steel nailing found in our previous experiment (Husby et al. 1989). This may partly be explained by the distal femoral growth in rats. Thus, the working length of the nail was reduced relative to the bone, and increased bending during physiologic loading induced increased strain of the anterior cortical wall. Further, the structural stiffness of the bone became closer to that of the nail, and a corresponding reduction in strain shielding was achieved.

Our in vitro results indicated that rigid as well as flexible medullary nailing for 12 weeks did not cause structural changes of the bones. This was also reflected by the normalized in vivo-strain measurements at Days 3 and 4 for the steel-removed femora. However, a larger reduction in stiffness was to be expected in the rigid nailed group. In an identical nailing model, Mølster (1986) found reduced strength and energy absorption (toughness) after 24 weeks with rigid nailing. Moreover, rigid intramedullary nailing of osteotomized and intact tibias from rabbits are reported to reduce the mechanical strength of bones secondarily (Kaartinen et al. 1985). Rigid nails may therefore cause alterations in other variables not included in our measurements.

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